Circulating Venous Bubbles in Recreational Diving: Relationships with Age, Weight, Maximal Oxygen Uptake and Body Fat Percentage

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Decompression sickness (DCS) is recognized as a multifactorial phenomenon depending on several individual factors, such as age, adiposity, and level of fitness. The detection of circulating venous bubbles is considered as a useful index for the safety of a decompression, because of the relationship between bubbles and DCS probability. The aim of this work was to study the effects of individual variables which can be assessed non invasively, on the grades of bubbles detected 60 min, after diving by means of Doppler monitoring, in a sample of 40 male recreational scuba divers. The variables investigated were: age, weight, maximal oxygen uptake ($\dot{V}O_2max$) and percentage of body fat (%BF). Bubble signals were graded according to the code of Spencer. The relationships between the bubble grades (BG) and the variables investigated were studied using two methods: the differences between the average values of each variable at each BG were analyzed by the Scheffe test. Then we performed the non-parametric Spearman correlation analysis. Significant differences ($P < 0.05$) were found (Scheffe test) between average values of the variables at grade 0 and 3 (age: $P = 0.0323$; weight: $P = 0.0420$; $\dot{V}O_2max$: $P = 0.0484$), except for %BF ($P = 0.1697$). Relationships with $P < 0.01$ were found (Spearman correlation) between BG and the variables: age: $\rho = 0.486$, $P = 0.0024$; weight: $\rho = 0.463$, $P = 0.0039$; $\dot{V}O_2max$: $\rho = -0.481$, $P = 0.0027$; except for %BF: $\rho = 0.362$, $P = 0.0237$. This work showed that bubble production after hyperbaric exposures depends on several idividual factors. The effects of age, weight and $\dot{V}O_2max$ are more significant than the effect of %BF. We concluded that to take into account such variables in decompression tables and diving computer programs should allow to adapt the decompression procedures to individual risk factors and reduce the DCS probability.

■ **Key words:** Recreational diving, bubbles, Doppler monitoring, age, weight, body fat percentage, maximal oxygen uptake.

Introduction

For more than 20 years it has been known, thanks to the Doppler ultrasonic detection, that post-dive decompression produces venous inert gas bubbles [19,33]. It was hypothesized that bubbles form in the tissues and blood during decompression as a result of supersaturation of the dissolved inert gas, from pre-exisiting gas nuclei due to vacuum phenomena [31]. Intravascular bubbles are detected in the venous circulation, most often in the precordial region, and their sound signals are graded according to a scale of assessment [15,30]. They are considered [25] as the most likely factor for initiating decompression sickness (DCS). Their presence is not sufficient to induce DCS, but it is known that DCS risk is correlated to bubble production [9,11,23,25,28,30]. Bove et al. [3] showed that a high grade of venous bubbles could increase the risk of neurological DCS. Thus, one can consider that the factors favouring the formation of bubbles are also DCS risk factors and it is possible to use the detection of circulating bubbles as an index of safety for dive and decompression profiles, and to investigate DCS risk factors in men, without any DCS symptom. Bubble formation during decompression, as well as DCS, are multifactorial and unpredicable phenomenons which Powell [26] called chaotic. Nevertheless, the incidence of individual characteristics such as age, weight, adiposity on DCS probability is widely recognized [8,13,17]. For Mebande and McIver [20], obesity and poor physical condition generally co-exist and represent a hazard to the divers. Obesity is recognized as a DCS risk factor because of the high solubility of nitrogen in lipids: Dembert et al. [8] found significantly higher measures of weight and skinfold thickness in USN divers who experienced DCS when compared to those who remained free of DCS. Carlioz et al. [5] showed significant effects of age, weight and body fat tissue on the grades of bubbles detected during decompression. For Lam and Yau [17], DCS susceptibility is increased by age, but this might be due to an increase of adiposity as a consequence of age. Broome et al. [4] reported that studies on military divers generally showed no association of DCS and age. They commented that, in military diving units, both senior and junior divers are required to maintain a high level of aerobic fitness. In the actual practice of diving, it is known that physical fitness is a determining biological factor

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for DCS probability, even if few studies showed its statistical significance. For Vann [32], aerobically trained runners appear to be at a lower risk of venous bubbling and bends than weight lifters or sedentary subjects. Gardette et al. [12] showed that divers who are "bubble producers" had lower scores at the Ruffier Index than "no bubble producers". Rattner et al. [27] found that aerobically trained rats had a significantly reduced risk of neurological DCS after hyperbaric exposure. McKirnan et al. [18] reported a reduction of 20% in cerebral blood flow (CBF) at rest, in a sample of exercise conditioned pigs, compared to the untrained control pigs. Broome et al. [4] hypothesized that such changes in CBF were representative of proportional changes in CNS blood flow generally, thus also in spinal blood flow. Therefore, they assumed that reduced spinal cord blood flow would lessen the gas uptake by spinal cord tissue and reduce the risk of neurological DCS. Moreover, they assumed that the rheological effects of aerobic training (a rise in plasma volume and fall in hematocrit) might also explain the reduction of the DCS risk. They also subjected pigs to an aerobic training program, and reported a significant reduction of the DCS incidence in the conditioned pigs, compared to the control sample, regardless of differences in age, adiposity and weight. When comparing various domestic non primate animals to man, the pig is the most physiologically similar [29]. So, Broome et al. [4] suggested that their findings in pigs might be extrapolated to human divers and that aerobical physical conditioning could protect them against neurological DCS. In order to provide data about relationships between bubble formation and individual variables which could be taken into account to improve the decompression procedures, we carried out Doppler monitoring after decompression in a sample of recreational divers. We investigated the relationships between bubble grades (BG) and variables non invasively assessed: age, body weight (kg), body fat percentage (%BF) and maximal oxygen uptake ($\dot{V}O_2$max), which is at present the best test to globally assess the adaptation to physical exertion [21]. We chose recreational divers because recreational diving practice increases in the world, and because the individual biometrical characteristics of the recreational divers are more dispersed than those of the military and professional divers whose adaptation to decompression is more studied and known. Previously, we have communicated preliminary results of our work at the 1996 and 1997 congresses of the European Underwater & Baromedical Society [6, 7].

Methods

Forty male recreational divers, medically fit to dive (mean age: 37 ± 10, mean weight: 80 ± 11 kg, mean height: 178 ± 5.8 cm) dived in open water at 35 metres of sea water (msw). They did not dive 48 h before the study dive and they were required not to dive if unfit or fatigued. The bottom time, including the descent time (70 s, i.e. 30 m × min^{-1}) was 25 min. The dives were performed on a 35 msw regular flat bottom. The decompression was determined in accordance with the COMEX 1987 decompression table: linear ascent at 9 m × min^{-1}, decompression stops: 3 min at 6 msw, 15 min at 3 msw. Ascent and decompression stops were not included in the dive time. The dive profiles and the rate of ascent were strictly controlled by one investigator who is a diving instructor and who performed all the dives himself. The temperature of the water varied in the period of the study from 15° to 20 °C at the surface, and from 12° to 16 °C at the bottom. The divers were equipped with neoprene diving suits in accordance with the water temperature. Thus, nobody reported to have suffered from the cold. They had to avoid any exertion except normal swimming during the dives, and to reduce exertion as much as possible before and after diving. All of them gave informed consent in accordance with the French law about bio ethics.

Bubble detection

Bubble detection was performed 60 min after surfacing using a continuous Doppler apparatus DUG COMEX PRO, equipped with a 5 MHz probe. This apparatus allows bubble detections (Ø ≥50 µm). Bubbles reflect a characteristic acute echo compared to the pulsed hiss corresponding to the blood flow [15]. To improve the accuracy of the cardiac signal, the subjects were placed in left lateral decubitus. The probe was placed in the precordial region, the ultrasonic wave being directed into the right ventricle. The subjects lay at rest 1 minute before the monitoring. Before the dives we performed a tape recording of their cardiac signal in order to have a reference. The signals were tape recorded for 2 minutes and graded in a blind manner by two independent investigators according to the Spencer Doppler code [29].

Assessment of maximal oxygen uptake

The maximal exercise test was performed in the Laboratory of Respiratory Function and Muscular Metabolism Exploration of the Sainte Marguerite Hospital (Marseilles).

Protocol:

Exercise was performed on a cyclo ergometer (ER 900 Jaeger). Testing sessions took place in the morning, 2 or 3 hours after breakfast. Ambient temperature ranged from 21° to 23 °C. After a 2 minutes warm-up period, the load was increased by 20 watts every 2 minutes. The test was stopped in case of exhaustion, excessive hypertensive reaction (diastolic pressure > 10 mmHg, systolic pressure > 25 mmHg), or when the subject presented two of the three accepted criteria of maximal exertion:

- maximal theoretical heart rate according to the Astrand formula: 200 puls. – age in years [2]
- respiratory ratio > 1.05
- no increase of $\dot{V}O_2$ although the minute respiratory flow kept increasing.

The following parameters were measured:

- oxygen uptake: $\dot{V}O_2$ STPD l × min^{-1} and ml × min^{-1} × kg^{-1} (kg = body weight),
- minute expiratory volume (VE BTPS l × min^{-1}), expired carbon dioxide ($\dot{V}CO_2$ STPD ml × min^{-1}), respiratory ratio (R = [$\dot{V}CO_2/\dot{V}O_2$])
- respiratory frequency.

The averages corresponding to the 1 minute intervals were displayed and the average of the second minute of each load level was retained for the study. Heart rate was recorded by means of standard electrocardiogram derivations during exertion and recovery periods. Systemic arterial blood pressure was measured at the end of each load level (Sphygmanometric).

Table 1 Individual variables and grades of bubbles

No.	Age	Weight	$\dot{V}O_2$max	%BF	BG	No.	Age	Weight	$\dot{V}O_2$max	%BF	BG
1	47	78	53	18.1	0	21	31	71	35	14.1	0
2	54	92	31.5	21.3	3	22	22	85	43.5	20.6	0
3	47	85	16.4	16.2	2	23	36	76	60.1	12.4	1
4	30	67	40.6	17.5	0	24	27	70	56	11.6	0
5	26	75	41.2	13.4	0	25	37	83	33.9	13.2	0
6	32	74	40.8	10.8	1	26	46	60	45.6	11.8	2
7	54	69	19.7	16.1	0	27	30	100	40.7	24.9	0
8	45	85	19.8	17.2	3	28	37	75	36	11.5	0
9	48	93	20.2	26.3	1	39	49	74	52.6	15.3	0
10	19	72	56	6.4	1	30	25	83	52.2	14	0
11	41	104	21.4	24.3	1	31	30	85	40.7	18.9	0
12	37	105	23.3	21.6	3	32	32	92	43.9	18.3	0
13	47	82	31.5	19	1	33	48	87	40.3	18.7	2
14	26	80	40	18.5	0	34	30	87	31	20.2	2
15	46	89	26.9	20.6	3	35	36	81	45	12.8	1
16	26	68	44	7.4	0	36	42	96	38.3	22	3
17	20	70	52.4	4.3	0	37	47	74	46.3	12.6	0
18	26	64	43.7	3.9	0	38	49	86	32	16.6	3
19	23	60	47.1	11.5	0	39	33	85	39.5	19	0
20	46	74	25.5	18.1	1	40	39	77	36.7	18.3	3

Measure of the percentage of body fat (%BF)

%BF was measured by electrical impedance by means of a Bodystat 1500 apparatus. This process is more accurate than the classical process of skinfold thickness [14,16].

Individual variables and bubble grades are shown in Table 1.

Statistical analysis

Data were analyzed with the statistical package STAT VIEW. BG are categorical and ordinal data, thus, to test the significant effect of each variable on BG, we performed a one-way analysis of variance (ANOVA) where BG were the categories between which we tried to make the differences evident. The significance between the average values of the variables at each BG was investigated with the Scheffe test. The relationships between BG and the variable average values were represented by regression lines. Then the correlations between variables and BG were investigated by the Spearman correlation analysis. The level for statistical significance was taken as: $P < 0.05$.

Results

Table 2 gives the average values of each variable within BG. The ANOVA showed the significance of age ($P = 0.0127$), weight ($P = 0.0381$), $\dot{V}O_2$max ($P = 0.0287$). %BF was not significant ($P = 0.1607$). The difference between the average values of all the variables was significant between grade 0 and grade 3, except for %BF (Table 3). The regression lines between BG and average values of the variables are showed in Fig. 1. The Spearman correlation test evidenced the significant effect of age, weight, $\dot{V}O_2$max and %BF (Table 4).

Table 2 Average values of the variables at each BG

BG (N)	Age	Weight	$\dot{V}O_2$max	%BF
0 (21)	32.286	76.571	42.952	14.510
1 (8)	38.125	82.000	37.563	16.263
2 (4)	42.750	79.750	33.325	16.725
3 (7)	44.571	90.000	29.786	19.657

Table 3 Significance of the differences between the averages values at each BG (Scheffe test)

BG	P for age	P for weight	P for $\dot{V}O_2$max	P for %BF
0 vs. 1	0.4945	0.6544	0.6610	0.8771
0 vs. 2	0.2268	0.9546	0.4081	0.8887
0 vs. 3	0.0323 S	0.0420 S	0.0484 S	0.1697
1 vs. 2	0.8713	0.9879	0.9275	0.9991
1 vs. 3	0.5946	0.5221	0.5476	0.6525
2 vs. 3	0.9911	0.4735	0.9587	0.8402

S = $P < 0.05$

Discussion

This study showed that individual susceptibility to bubble production during decompression depends on individual characteristics such as age, body weight, aerobic fitness and body fat. The effect of %BF was less significant than the effect of the other variables. At present no data in the literature show a relationship between $\dot{V}O_2$max and bubbles. Our findings are consistent with the studies carried out on animals [4,27], which reported the influence of exercise conditioning on DCS occurrence. Bubble formation is a multifactorial process (see

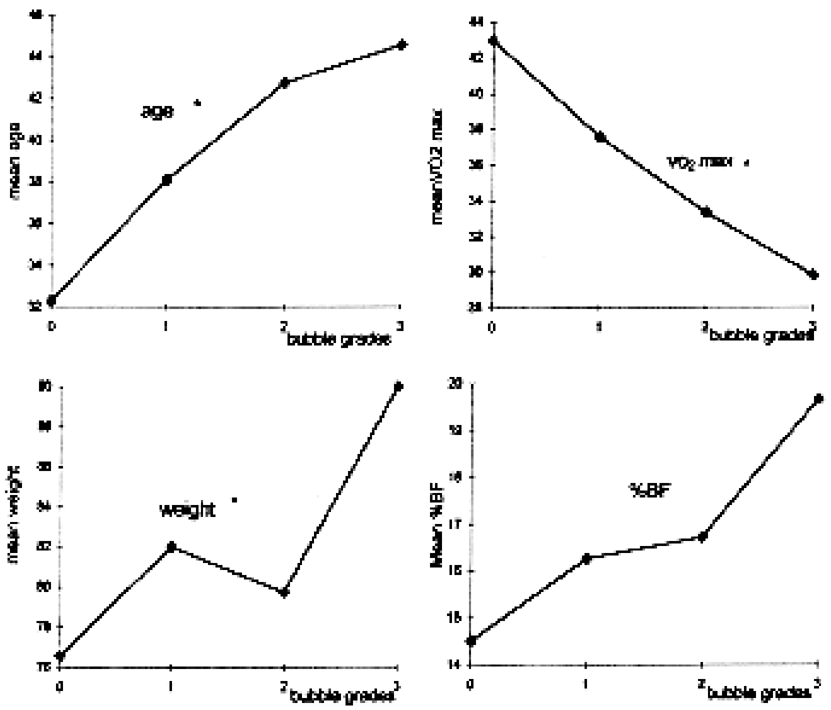

Fig. 1 Relationships between bubble grades and variables: the difference between the average values of age, weight, and $\dot{V}O_2$max is significant ($P < 0.05$) at grade 0 and grade 3 (*).

Table 4 Spearman correlation between BG and variables

BG vs. age	BG vs. weight	BG vs. $\dot{V}O_2$max	BG vs. %BF
$\rho = 0.486$ $P = 0.0024$ S	$\rho = 0.463$ $P = 0.0039$ S	$\rho = -0.481$ $P = 0.0027$ S	$\rho = 0.362$ $P = 0.0237$ S

S = $P < 0.05$

Table 5 Correlations between variables

	Age	Weight	$\dot{V}O_2$max	%BF
Age		0.257 NS	0.521 S	0.443 S
Weight			-0.464 S	0.780 S
$\dot{V}O_2$max				0.547 S

S = $P < 0.05$

introduction). Thus, although it was not strictly statistically correct, we believed that it could be interesting to perform a multiple regression analysis including all the variables, in order to realize a snapshot of the respective part of each variable. The 4 variables were the independent variables and BG was the dependent variable. The results were: 4 variables: $P = 0.0016$, age: $P = 0.0183$; weight: $P = 0.0480$; $\dot{V}O_2$max: $P = 0.2431$; %BF: $P = 0.2422$. This analysis, whose significance threshold was $P < 0.05$, showed more significance for age and weight than for $\dot{V}O_2$max and %BF. Except for age and weight, the variables are correlated to one another (Table 5). For Zar [35], in such a case, the interpretation of partial regression becomes questionable, this could explain that age and weight took all the significance.

We concluded that recreational divers would be well advised to keep themselves physically fit by means of aerobic training, in order to reduce bubble formation and DCS risk during decompression. Moreover, through training, elderly divers will also reduce their body fat rate, and will doubly improve their safety. Our conclusion is consistent with Broome et al. [4], who underlined that an individual could manipulate his personal risk by being aerobically fit or unfit. Moreover, divers with a high probability of DCS risk must use decompression tables or procedures which take these risks into account. They must not use military decompression schedules tested by military divers: Aharon-Peretz et al.[1] emphasized the high incidence of neurological DCS reported in civilian usage of military diving tables. Age, weight, maximal oxygen uptake and body fat percentage should be taken into account to adapt decompression tables and dive computer programs. The physicians could use such data to classify the divers into risk probability categories. As Moon et al. wrote [22]: "Someday, diving computers based on probabilistic models should reflect this reality (individual characteristics*) by enabling divers to declare the probability they are comfortable with and then conduct their dives accordingly". It is evident that our statistical analysis does not explain all the aspects of bubble formation. Other variables such as blood factors [34] are also recognized as being an influence. However, we chose to check variables which can be assessed non invasively. The delay of 60 min before Doppler monitoring was imposed due to particular material circumstances. Nevertheless, some authors reported that in most cases, bubbles peak about 60 min after surfacing [10,25], so we can assume that this delay was appropriate. Unlike experimental studies in hyperbaric chambers, our subjects had to exercise under actual conditions of diving, i.e. to equip themselves, to swim, to come back to the diving boat, to take off and tidy their equipment, etc.... They were affected by the effects of cold and immersion: diuresis, haemoconcentration, change in the repartition of the blood mass, dehydration. Thus, their level of bubble release corresponded to the actual exercise of all recreational divers respecting the safety rule: moderate exertion before, during and after diving. Thus, we consider that the field conditions of our study give a better picture of the bubble production than the traditional experimental studies carried out in hyperbaric chambers on standard samples of professional or military divers.

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